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Two-Layer Film as a Laser Soldering Biomaterial

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Background and Objectives: **A two-layer solder was developed to weld at low laser intensity and to provide a new method of measuring solder-tissue temperature.**

Study Design/Materials and Methods: **A film solder consisted of a white layer (bovine serum albumin (BSA) and distilled water) and a black layer (BSA, carbon black (CB), and distilled water). This two-layer solder was used with a diode laser to weld sections of dog small intestine (λ = 810 nm, power = 200 ± 20 mW, radiation dose = 18 ± 1 J/mg). Sections of intestine were welded only with one-layer black solders as control group. The temperature difference between the external solder surface and the tissue-solder interface was evaluated during welding.**

Results: **The two-layer solder performed welds as strong as the one-layer solder (~0.12 N) but with less laser intensity on the black layer. The temperature difference between the external surface of the solder and the solder-tissue interface was significantly less for the two-layer solder than for the one-layer solder (~6°C and ~15°C, respectively; $P < 0.05$).**

Conclusions: **The two-layer solder appeared to be more efficient at soldering biomaterials than the one-layer solder. Furthermore, the heat diffusion from the black midplane of the two-layer solder decreased the difference in temperature recorded on the solder external surface and on the solder-tissue interface. Lasers Surg. Med. 25:250–256, 1999.**

Key words: tensile strength; temperature control; mechanical properties

INTRODUCTION

Laser protein glues are a promising alternative to conventional sutures for approximating tissue together [1–6]. A major limitation of these glues is the mechanical weakness of their tissue bond, acutely and during the first week postoperation [7,8]. In particular, albumin solders have mechanical properties inferior to those of sutures when lasers activate them [9]. The laser intensity, for example, can vaporize part of the solder and create air bubbles inside it, which weaken the solder structure [10]. Decreasing the solubility of solders in physiological fluids can better preserve their integrity during laser welding procedures. In a previous study, the increase of albumin concentration was proved to decrease the solubility and to enhance the mechanical properties of solid albumin solders, prior to laser irradiation [11]. The tensile strength of laser-repaired tissue was also reported to be increased when sodium hyaluronate was added to the albumin glue [12]. Albumin solders may also be steamed by warm water vapors to partially denature them and to increase their elasticity [13,14]. Whatever method is used to enhance the mechanical properties of the solder, its laser-gluing faculty must be pre-

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TABLE 1. Parameters for Laser-solder Repairs*

	Solder (type)	Thickness (mm)	Area (mm^2)	Power (W)	Time (sec)	Dose (J/mg)	Strength (N)
Group 1, 72% BSA + 0.39% CB	OL (n = 10)	0.15 ± 0.01	4.2 ± 0.2	0.12 ± 0.02	102 ± 3	18 ± 1	0.124 ± 0.033
	TL (n = 10)	0.15 ± 0.01	4.7 ± 0.4	0.12 ± 0.02	114 ± 8	18 ± 1	0.129 ± 0.036
Group II, 72% BSA + 0.25% CB	OL (n = 10)	0.15 ± 0.01	4.6 ± 0.7	0.20 ± 0.02	65 ± 9	18 ± 1	0.107 ± 0.029
	TL (n = 10)	0.15 ± 0.01	4.3 ± 0.5	0.20 ± 0.02	63 ± 6	18 ± 1	0.122 ± 0.019
Group III, 72% BSA + 0.39% CB	OL (n = 10)	0.10 ± 0.01	3.9 ± 0.6	0.15 ± 0.02	54 ± 7	20 ± 1	0.071 ± 0.016
	TL (n = 10)	0.11 ± 0.01	4.4 ± 0.3	0.15 ± 0.02	67 ± 7	19 ± 1	0.052 ± 0.020

**Solder,* type of solder; *OL,* one-layer solder; *TL,* two-layer solder; *n,* number of repairs; *Thickness,* thickness of solder strips; *Area,* surface area of the strips; *Power,* laser power; *Time,* time of laser irradiation; *Dose,* laser energy per mass of solder; *Strength,* force required to break laser-solder repairs.

served. In this report, a two-layer (TL) solder was studied, which preserved its mechanical structure after being lasered and which performed efficient tissue welds. Also, the TL solder provided a new method of measuring the solder-tissue temperature during laser welding.

MATERIALS AND METHODS

Two-Layer Solder

Two solder films were pressed by a parallel plate vice to form a single TL film. One solder layer (white layer) contained 72 ± 2% bovine serum albumin (BSA) and distilled water (by weight). The other layer (black layer) contained 72 ± 2% BSA, 0.25 ± 0.06% or 0.39 ± 0.08% carbon black (CB), and distilled water. The thickness of the white layer and black layer was approximately half the total TL film thickness (0.110–0.150 mm). The protein film was cut in small rectangular pieces (strips) by a no. 10 surgical blade. Each layer of the TL film was prepared as described in a previous study [15], and its thickness was measured by a digital caliper (SD = 0.01 mm).

In Vitro Tissue Welding

A GaAs diode laser (λ = 810 nm) was used in conjunction with the protein strips to weld sections of dog small intestine (~2 × 1 × 0.3 cm). The tissue was harvested the same day of the laser repair. These sections were cut along the middle line and repaired end-to-end with the TL solder or with the black one-layer solder (OL solder). Two strips (dimensions, ~3.5 × 0.6 × 0.15 mm) were positioned across the intestine middle incision and they partially dissolved on the tissue moisture, still retaining their shape [11]. As the strip was lasered, the liquefied part of the solder was welded to the serosa. A multimode silica fiberoptic (core diameter = 400 μm) delivered the beam in a continuous wave onto the solder with a spot size of ~500 μm. The black layer of the TL solder was positioned onto the tissue to absorb the laser beam and efficiently transmit the generated heat to the tissue-solder interface [16]. All the tissue repairs were performed under an operating microscope (×20). The intestine repairs were divided into three groups to compare the welds of the TL and OL solders at different power levels, solder thickness, and CB concentrations. The irradiation dose (J/mg) was kept constant in each group (Table 1).

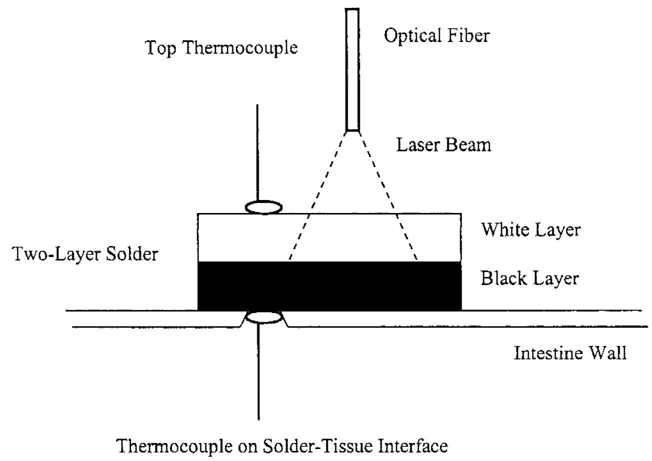

Fig. 1. Side view of setup for measuring solder temperatures during laser welding. Two thermocouples were placed on opposite sides of the solder, which was over the intestine wall (serosa). The laser bean was directed onto the solder strip without shining on the top thermocouple.

Repair Strength and Histology

The soldered intestine was tested acutely to assess the strength of the repair by using a calibrated tensiometer (Instron Mini 55, MA), interfaced with a personal computer. The specimen was clamped to the tensiometer by pneumatic grips, which moved 22 mm/minute until the sol-

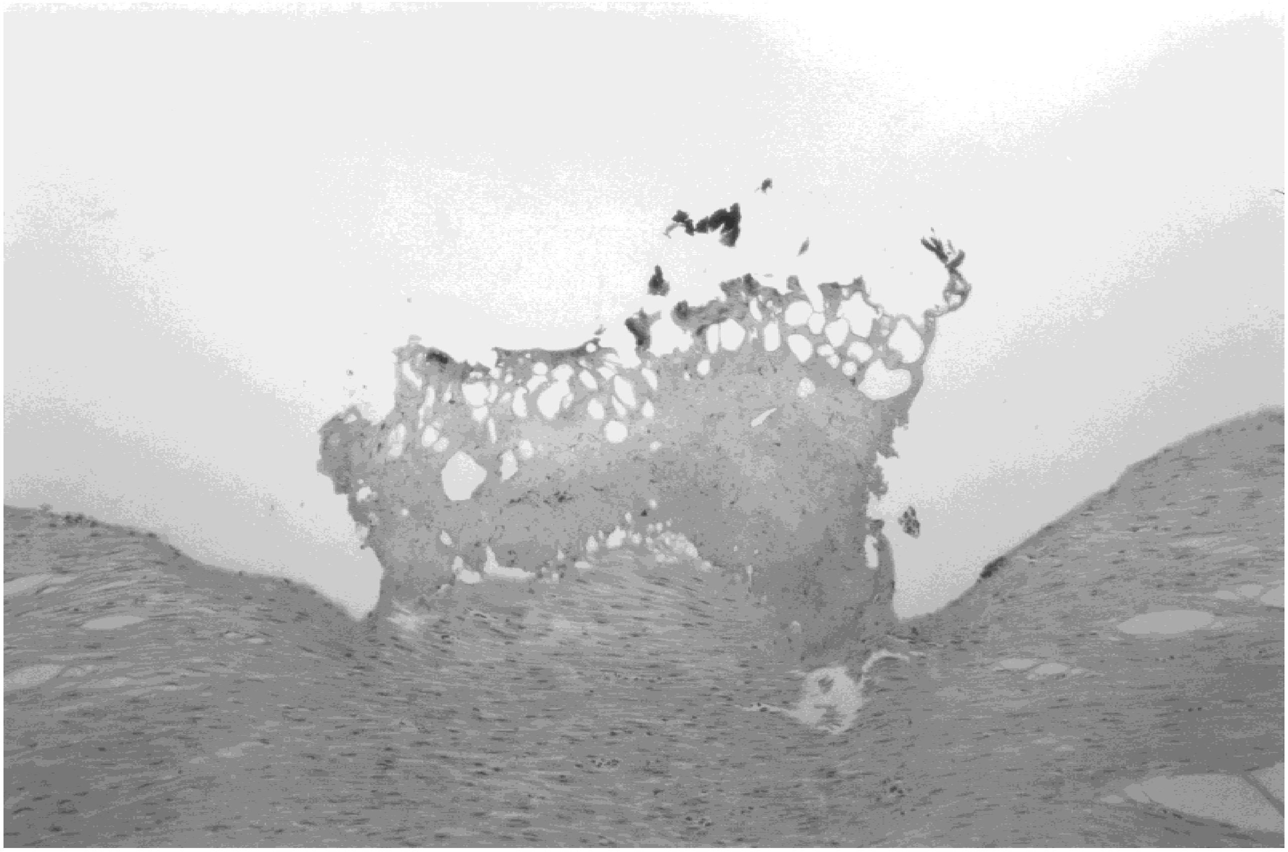

Fig. 2. Transverse section of a *one-layer* strip, which was laser-welded to the serosa layer. Granules of carbon black are scattered throughout the solder (black dots). The air bubbles are concentrated at the top of the solder, as the laser irradiated it. The strip is partially disrupted because of vaporization and carbonization of its upper part (H&E, ×100).

der weld failed, by separating the two intestine segments. The tissue was kept wet throughout the procedure, since the tensile strength increased by drying [10]. The breaking force was recorded.

Three welds were performed in each group for histological evaluation. The samples were fixed in 10% formalin solution and stained with hematoxylin and eosin (H&E) or Masson's trichrome.

Solder Infrared Absorption

To assess laser attenuation in the solder, a spectrophotometer (Shimadzu UV-1201) measured separately the absorbance (accuracy and repeatability = ± 0.007) of the black and white solder film at 810 nm (resolution = 5 ± 0.5 nm). The extinction length (90% of laser attenuation) was calculated from the solder absorbance, by assuming the validity of Beer's law.

Temperature Measures

One strip of solder was welded onto extra sections of intestine (n = 30), as described previously. The strips comprised one or two layers and their dimensions were approximately 3.5 × 0.8 × 0.15 mm. The temperature difference (ΔT) between the lasered solder surface and the solder-tissue interface was measured by two K-type thermocouples during laser welding (Fig. 1). One thermocouple was passed through the intestine wall in order to be in contact with the bottom part of the solder strip. The two thermocouples (temperature range from –204°C to 404°C, diameter = 0.5 mm, response time = 0.1 seconds) were fixed symmetrically on the opposite sides of the strip and the laser irradiated the top solder surface without shining on the thermocouple, which was sensitive to the laser beam. Each thermocouple was connected to a multimeter, which displayed the solder temperatures. Both thermocouples recorded 22 ± 1°C prior to laser irradiation. The strip was irradiated for 30 seconds, and its temperatures were recorded every 10 seconds. The irradiation time was decreased with respect to the previous laser solder welds, as ~⅓ of the solder surface was occupied by the thermocouple setup.

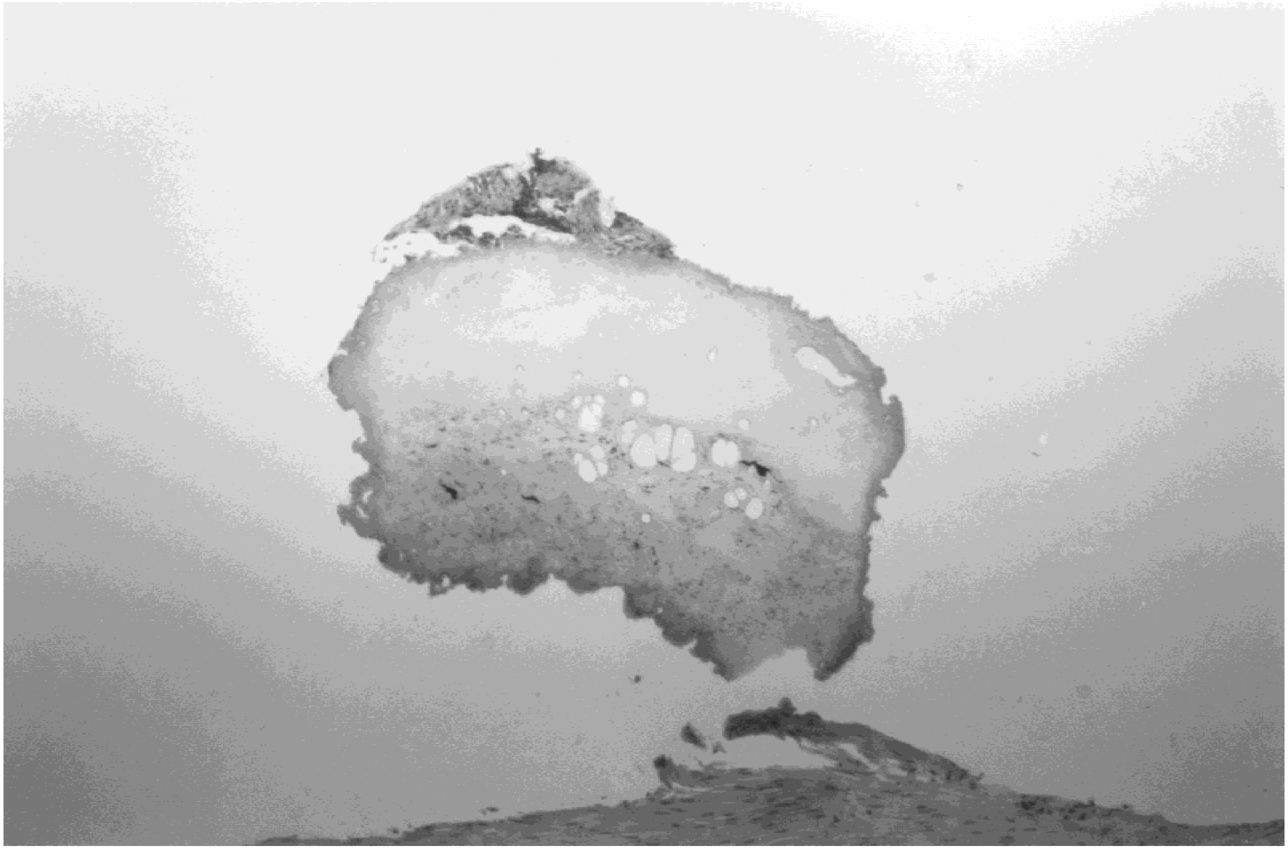

Fig. 3. Transverse section of a *two-layer* strip after laser welding with the serosa layer (bottom of picture). The lower half of the solder contains scattered granules of carbon black (black dots), while the top half does not (whitish appearance). The air bubbles (generated by the laser heat) are localized mostly in the middle of the strip (black middle plane), and they are scattered on both layers of the solder. The strip substantially preserves its integrity. Tissue manipulation during slide preparation detached the strip from the serosa layer (H&E, ×100).

Statistical Analysis

Statistical comparison of means was made using Student's t-test for unpaired observations (0.05 level of significance). The histograms were generated by Sigma Plot (2.01 version).

RESULTS

Repair Strength and Histology

There was no significant difference ($P > 0.05$) between the breaking force of the TL and OL solder repairs, within groups I and II (Table 1). However, The OL solder performed stronger repairs than the TL solder in group III ($P = 0.03$). The OL solder suffered disruption and ablation on its top, where many air bubbles were localized (Fig. 2). On the other hand, the TL solder preserved its structure almost intact; some air bubbles were localized in the solder middle plane and on both layers (Fig. 3). Abundant black fumes were observed during laser welding of the OL solder, while almost no fumes were present with the TL solder repairs.

Solder Infrared Absorption

The solid solder containing no CB had an extinction length of 0.187 ± 0.029 mm due to light scattering. The extinction length of the black solder was shorter and it increased from 0.051 ± 0.006 mm to 0.070 ± 0.004 mm as the CB concentration inside the solder decreased from 0.38% to 0.25% (Table 2).

Measures of Temperature

The temperature difference between the external solder surface and the tissue-solder interface was significantly lower ($P < 0.05$) for the TL solder (~6°C) than for the OL solder (~15°C). These data are summarized in Figure 4. The external temperature of the OL solder (~ 40°C) was lower than expected [17] because the thermo-

TABLE 2. Adsorption Data of Solder at a Wavelength of 810 mm, Giving Mean Value ± Standard Deviation*

CB% (g/g)	n	Absorption	Thickness (mm)	Extinction length (mm)
0	3	0.968 ± 0.289	0.18 ± 0.06	0.187 ± 0.029
0.25 ± 0.06	3	2.376 ± 0.069	0.17 ± 0.01	0.070 ± 0.006
0.38 ± 0.08	3	2.584 ± 0.139	0.09 ± 0.01	0.050 ± 0.006
0.38 ± 0.08	3	1.748 ± 0.218	0.14 ± 0.02	0.053 ± 0.007

*Each solder sample contained 72 ± 2% BSA, carbon black (as specified), and distilled water (remnant percentage). *CB,* carbon black concentration of the solder in percentage (by weight); *N,* number of solder samples analyzed; *Absorption,* absorption of solder sample; *Thickness,* thickness of solder sample; *Extinction length,* extinction length of solder sample.

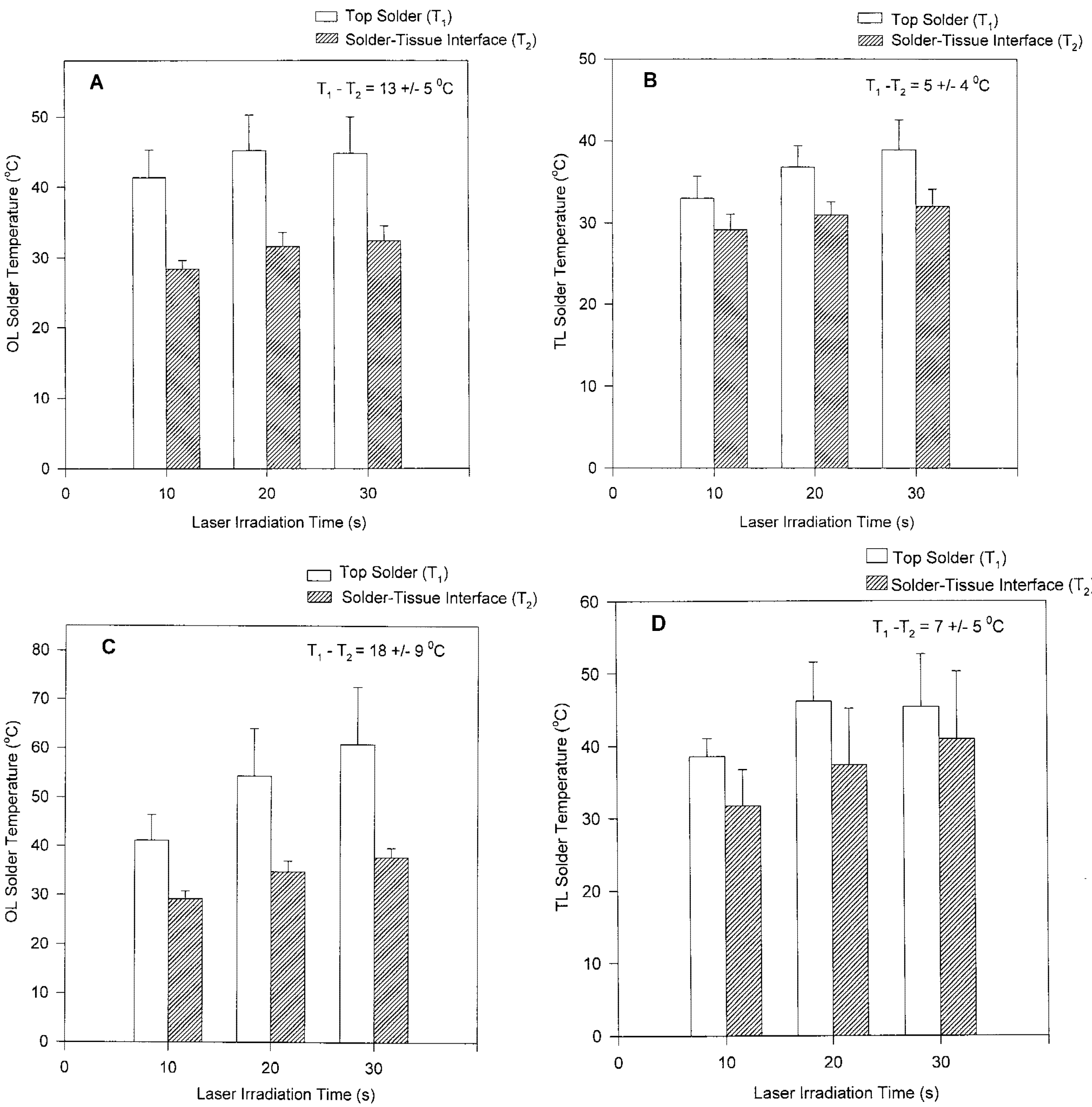

Fig. 4. Temperatures of the top solder (T_1) and the solder-tissue interface (T_2) vs. the laser irradiation time. T_1–T_2 represents the average difference of temperature ΔT) over 30 sec (± standard deviation). **A:** The laser irradiated at a power level of 0.16 ± 0.02 W onto the *one-layer* solder (0.39 ± 0.08% CB). Eleven welds were performed. **B:** The laser irradiated at a power level of 0.16 ± 0.02 W onto the *two-layer* solder (0.39 ± 0.08% CB). Nine welds were performed. **C:** The laser irradiated at a power level of 0.20 ± 0.02 W onto the *one-layer* solder (0.25 ± 0.06% CB). Five welds were performed. **D:** The laser irradiated at a power level of 0.20 ± 0.02 W onto the *two-layer* solder (0.25 ± 0.06% CB). Five welds were performed.

couple was in contact with the solder in a fixed position, which was never directly irradiated [18]. Therefore, the ΔT of the OL solder was underestimated but the ΔT of the TL solder was accurate, as the black lower layer absorbed the laser beam. The heat generated in the black layer of the TL solder traveled a similar path in both layers before reaching the thermocouples, which were placed symmetrically apart with respect to the black midplane (Fig. 1).

DISCUSSION

The tensile strengths of the OL and TL solders were similar (~0.12 N), when laser power and energy dose were kept constant. However, less laser intensity (W/cm^2) was required on the black layer for the TL solder repairs (groups I–II). In these repairs, the laser path was increased by half the solder thickness (the white layer) prior to the CB absorption, demonstrating less laser intensity. The laser-generated heat diffused only half the thickness before reaching the solder-tissue interface, while the heat had to diffuse the whole thickness to weld the OL solder to the tissue. The OL solder suffered laser vaporization, ablation, and sometimes carbonization of its top (Fig. 3). This was due to the high laser intensity, which was necessary to transmit part of the laser energy (transformed into heat) down to the tissue. On the other hand, the TL solder remained intact after irradiation, as the laser intensity on the black layer decreased by beam divergence and scattering. In this respect the TL solder appeared to be a more efficient soldering biomaterial than the OL solder. The thickness of the TL solder could not be decreased (~0.110 mm) to enhance the heat diffusion to the tissue, as the tensile strength dropped to ~0.06 N in group III. It is likely that the scattered light in the solder decreased the energy absorbed by the thinner black layer, weakening the solder repair. In this group, the OL solder achieved stronger repairs than the TL solder, as the black thickness of the TL solder was not greater than but approximately equal to its extinction length (~0.05 mm).

The heat diffusion from the black midplane of the TL solder decreased the difference in temperature (~6°C) recorded on the solder external surface and on the solder-tissue interface. The heat diffusion was partially symmetric, as proved by the air bubbles scattered on both layers of the strip (Fig. 2). The air bubbles were localized only on the top of the OL solder, in which the heat diffused from the top to the bottom (Fig. 3). The heat diffusion inside the TL solder was not perfectly symmetrical (with respect to the black midplane), causing the temperature difference mentioned above. Indeed, a very thin and efficient absorbing layer should be placed between two white layers of solder to achieve a more symmetrical diffusion. Also, the top layer of the TL solder was hotter than its bottom layer, as the tissue conducted and absorbed heat while the air surrounding the top layer did not. The TL solder, therefore, provided a new method of measuring the solder-tissue temperature by measuring the external solder temperature [17,18]. For this purpose, thermal control systems may be efficiently coupled with TL solder during tissue welding.

In prospective, solders comprising two or more layers may be beneficial to approximate tissue together. Indeed, the layer in contact with the tissue may serve to weld, and the others may deliver antibiotics, growth factors, or genes to improve tissue-healing [8]. Further studies are underway to test the decreased temperature (ΔT) across the TL solder by using a thermal control system.

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